Damping Optimum-based Design of Direct-Current Microgrid Voltage Control System with Disturbance and Fault Robustness Analysis

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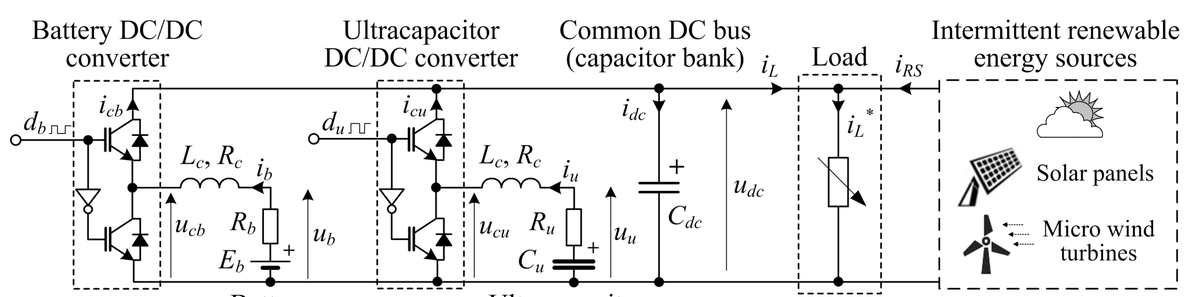
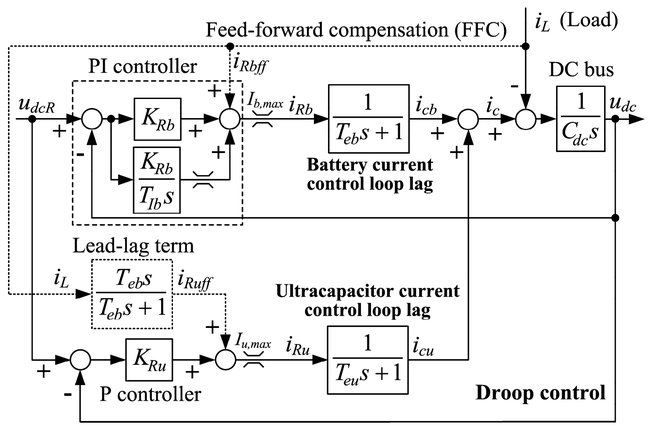
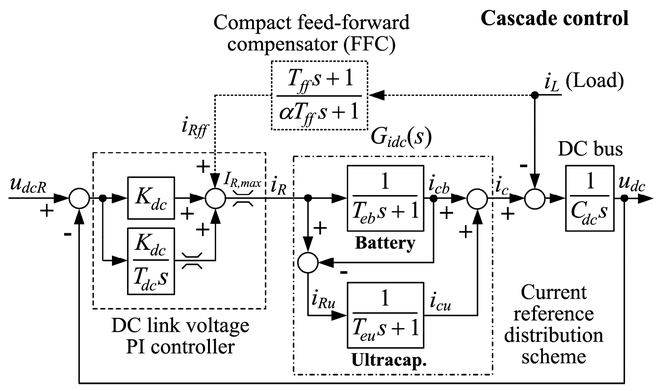
- **A design of a hybrid battery/ultracapacitor energy storage system (ESS) DC microgrid control system is based on droop and cascade control.**
- **The proposed control systems are augmented by feed-forward load compensators aimed at achieving effective load disturbance rejection.**

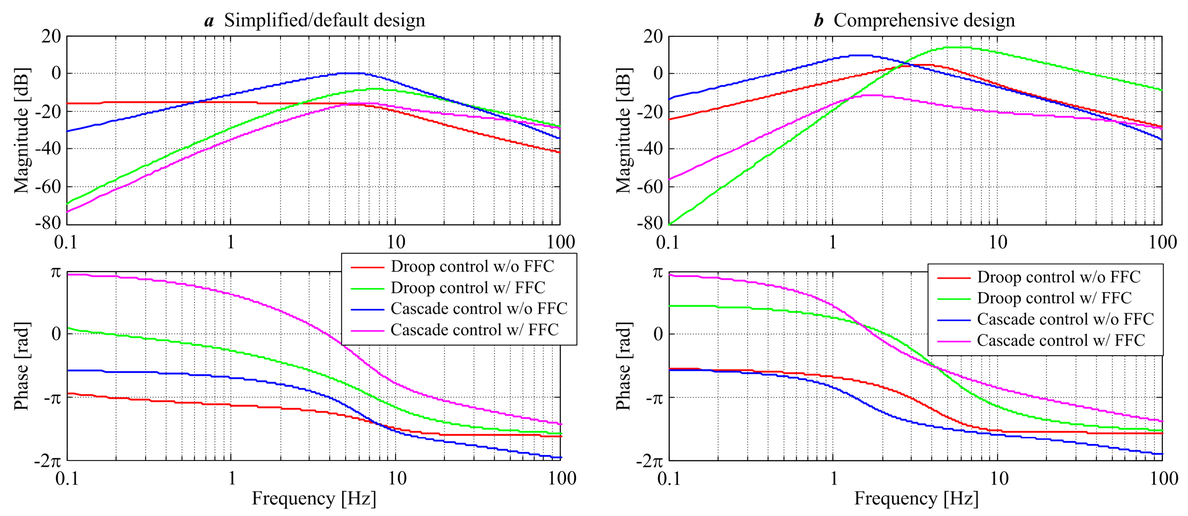


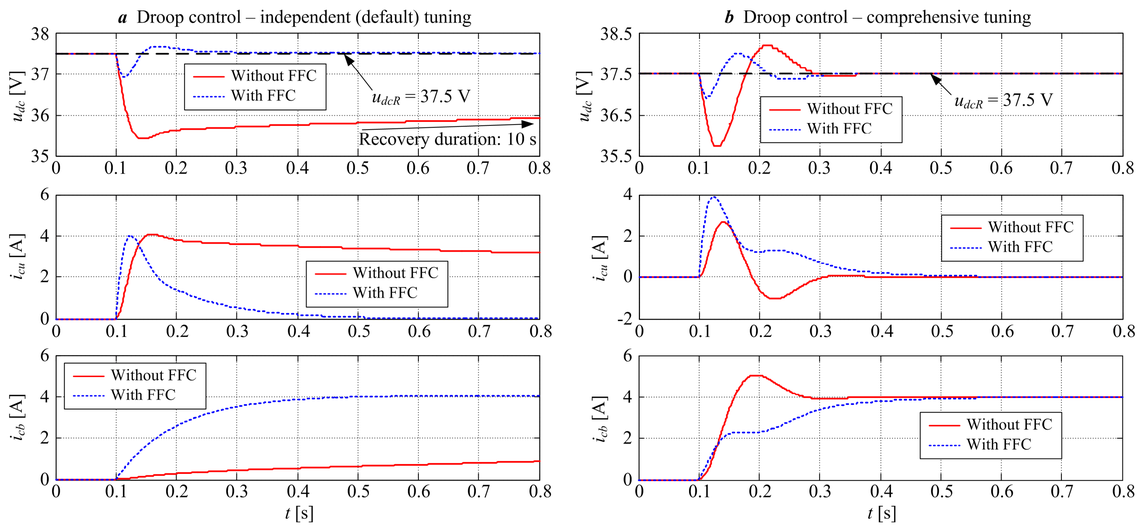


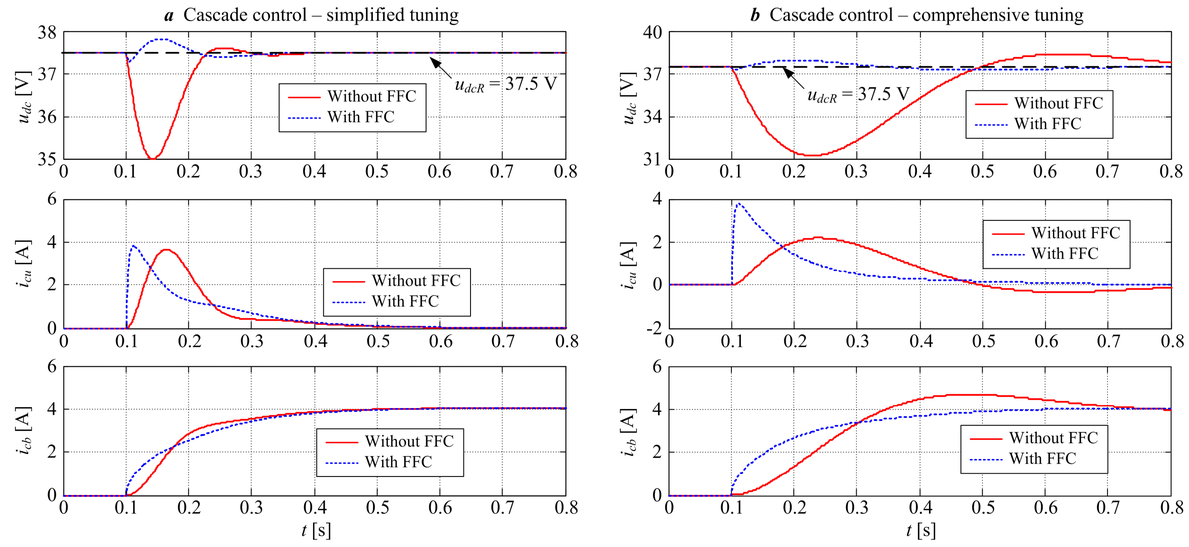


- **The control systems have been designed based on the damping optimum criterion, which results in straightforward and analytical expressions for individual controller parameters.**
- **In the case of droop control system, controller tuning can be performed independently (default case) or by utilizing a comprehensive tuning approach.**
- **Cascade control system design may be based on simplified or comprehensive model of the inner-level DC bus load distribution.**

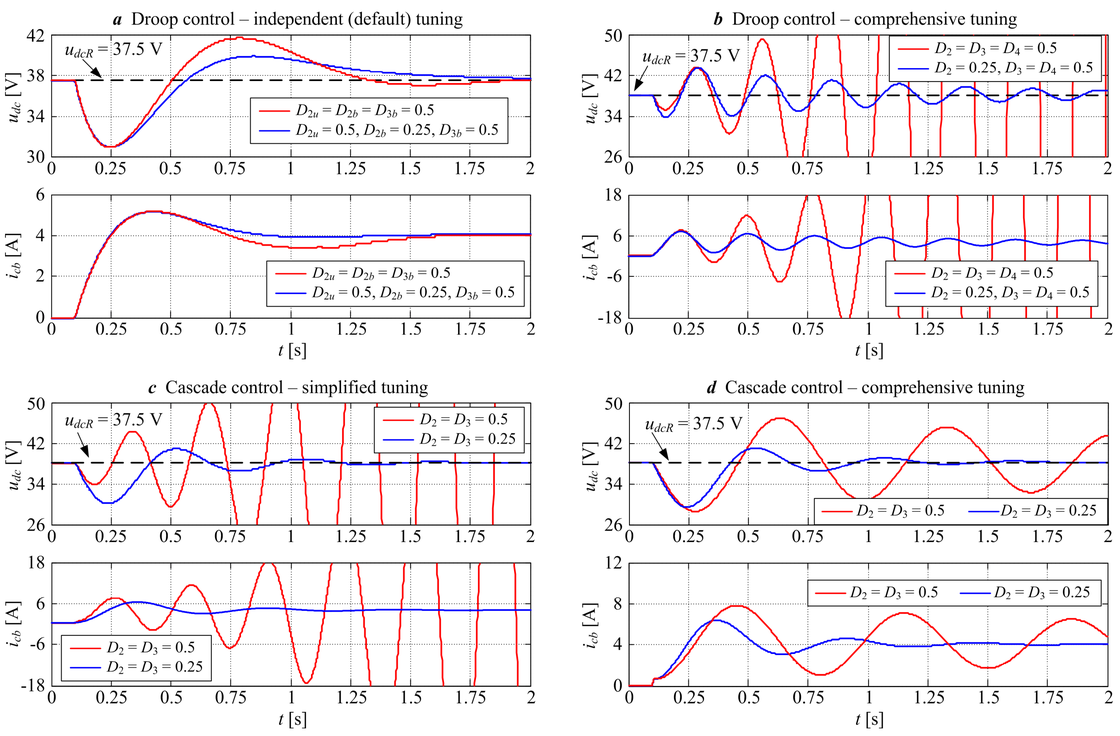
- **The effectiveness of different control schemes is investigated via closed-loop system frequency characteristics.**
- **Purely feedback-based systems (no feed-forward compensation) are characterized by rather inferior suppression of load disturbance in the low-to-middle frequency region.**
- **By introducing the feed-forward action, the low-frequency attenuation of load disturbance is significantly improved.**
- **A significant phase lead behavior is also obtained: should result in fast load response and small perturbations if DC bus voltage.**







- **Utilization of feedback controllers alone indeed results in relatively large voltage drops and may also result in prolonged DC bus voltage recovery.**
- **By introducing the load feed-forward compensation action, the voltage drop magnitude can be reduced by an order of magnitude, and very fast load disturbance recovery can be achieved.**



- **Ultracapacitor ESS fault scenario:**
  - **Default design of droop-control system (independently tuned ultracapacitor and battery controllers) assures robust behavior and preserved favorable damping of the overall closed-loop system. However, this is achieved with less effective load suppression performance due to the absence of fast ultracapacitor action.**
  - **In the case of comprehensive droop-control system design and simplified cascade control system design, unstable closed-loop behavior is obtained for the optimal tuning according to damping optimum criterion. Closed loop stability is obtained for sub-optimal tuning parameter choice.**
  - **The cascade control system based on the comprehensive PI controller tuning approach is characterized by weakly damped (oscillatory) response for the optimal tuning parameter choice. Its closed-loop damping is notably improved when tuned for sub-optimal behavior.**
- **Final recommendation:**
  - **Droop-control system with independent tuning of ultracapacitor and battery ESS controllers, and equipped with feed-forward compensator should be the most suitable choice which guarantees robust performance under ultracapacitor ESS faults.**

	Default/simplified design		Comprehensive design	
Droop control:	**Optimal**	**Sub-optimal**	**Optimal**	**Sub-optimal**
Recovery time t_r [s]	0.41	0.46	N/A (unstable)	**0.12 (oscillatory)**
Voltage drop $\Delta u/u_{dcR}$ [%]	16.80	16.96	N/A (unstable)	**8.27**
Cascade control:	**Optimal**	**Sub-optimal**	**Optimal**	**Sub-optimal**
Recovery time t_r [s]	N/A (unstable)	0.32	0.36 (oscillatory)	**0.33**
Voltage drop $\Delta u/u_{dcR}$ [%]	**N/A (unstable)**	**22.67**	**27.60**	**21.07**

The presented research has been conducted within the activities of the Center of Research Excellence for Data Science and Cooperative Systems supported by the Ministry of Science and Education of the Republic of Croatia.